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ABSTRACT

Since the signature from the Partial Defect Detector (PDET) is principally dependent on the geometric layout of the guide tube locations, the capability of the technique in detecting symmetric diversion of pins needs to be determined. The Monte Carlo simulation study consisted of cases where pins were removed in a symmetric manner and the resulting signatures were examined. In addition to the normalized gamma-to-neutron ratios, the neutron and gamma signatures normalized to their maximum values, were also examined. Examination of the shape of the three curves as well as of the peak-to-valley differences in excess of the maximum expected in intact assemblies, indicated pin diversion. A set of simulations with various symmetric patterns of diversion were examined. The results from these studies indicated that symmetric diversions as low as twelve percent could be detected by this methodology.

INTRODUCTION

Various attempts have been made in the past two decades to develop a technology to identify a possible diversion of pins and to determine whether some pins are missing or replaced with dummy or fresh fuel pins. However, to date, there are no safeguards instruments that can detect a possible pin diversion scenario that meet the requirements of the IAEA. The FORK detector system [1-2] can characterize spent fuel assemblies using operator declared data, but it is not sensitive enough to detect missing pins from spent fuel assemblies (SFAs). Likewise, an emission computed tomography system has been used to try to detect missing pins from a SFA [3]. This has shown some potential for identifying possible missing pins but the capability has not yet been demonstrated, especially in an inexpensive, easy to handle setting for field applications.

A novel methodology is being developed to detect partial defects in PWR spent fuel assemblies without relying on any input from the operator. This involves inserting tiny neutron and gamma detectors into the guide tube locations, measuring the signals and processing them to form normalized signals of the neutron and gamma responses and the gamma-to-neutron ratios. Earlier papers detailed the development of this unique signature that will be noticeably perturbed if some of the fuel pins are replaced with dummy pins both in isolated SFAs as well as SFAs in an in-situ condition in the storage racks [4, 5]. Another paper in this conference will discuss the benchmarking of this methodology against measurements taken in SFAs with pins missing [6]. The simulation and experimental results compared well thus validating the technique.

Since the base signature from PDET is essentially symmetric and primarily dependent on the geometric layout of the guide tubes, there is a need to examine the response of the system in the event pins are removed in a symmetric fashion. This study will examine cases of symmetric pin diversion from SFAs both in an isolated condition as well as those in an in-situ condition in their storage rack positions. The in-situ model will use 5x5 configurations of SFAs with the test SFA in the center of this configuration. Comparison will also be made between 3x3 in-situ studies and 5x5 in-situ cases to determine the impact of surrounding SFAs on the test assembly.

COMPUTATIONAL MODEL

The base model for this study will continue using 14x14 PWR fuel that was used in the previous studies [4, 5]. However, this study will mainly use SFAs with uniform burnup since this would constitute a very difficult scenario if pins are removed in a symmetric manner. Studies with non-uniform burnup test SFAs will also be discussed.

A SFA with initial enrichment of 3.2 w% U-235 and a burnup of 32 MWd/kg was selected for the uniform burnup cases. The fuel was depleted on a single pin basis for 856 days using ORIGEN-ARP [7] to the desired burnup level by adjusting the power in the pin. The gamma and neutron source terms and spectra and isotopics were obtained from these calculations at a cooling time of 26 years. The boron concentration in the pool was 2000 ppm. The list of isotopes used was pared down to 41 (both fission products and actinides) that represented the principal absorbers [8]. Figure 1 shows this test assembly surrounded by SFAs in a checkerboard pattern of uniform lattices of 26 and 36 MWd/kg burnups. The SFAs are in a high density storage rack with a stainless steel frame and boral (~ 4mm). For pin diversion scenarios the missing fuel pins were replaced by stainless steel rods.

The MCNP [9] calculations were performed in the fixed source mode using the latest available ENDF/B-VI data sets [10]. Two separate runs were made: a coupled neutron-gamma run using the neutron source terms and gamma run using the gamma source term. It must be noted that the neutron induced gamma contribution is negligible in these situations compared with the fission product decay gammas. Neutron and gamma fluxes were obtained at the sixteen guide tube locations (identified by the 16 symmetric squares in the center test assembly in Figure 1) where the measurements would be made. All relevant results had standard deviations of less than 0.5%.

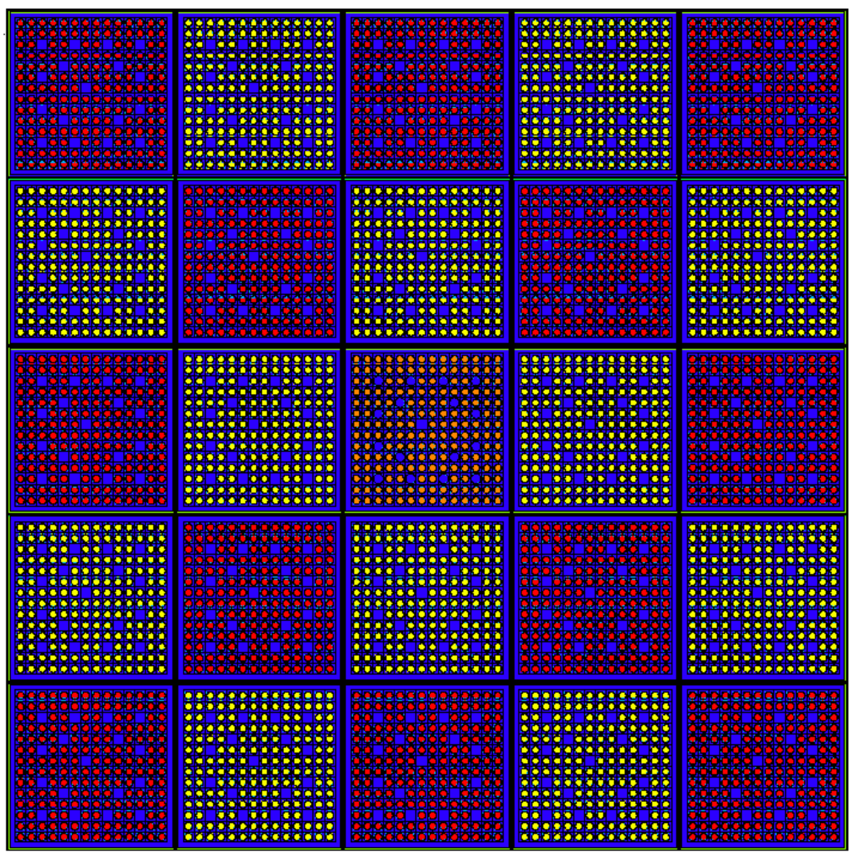

Figure 1. 5x5 Spent Fuel Assemblies in Storage Rack

ANALYSIS OF SINGLE ASSEMBLY CASES

In addition to the SFA with uniform burnup, a lattice with a burnup gradient ranging from 26 MWd/kg to 36 MWd/kg [4, 5, 6] was also examined in the isolated case. Twenty eight fuel pin, representing 16% of missing fuel, were removed in a symmetric manner in the center of the SFA. Figure 2 shows the pattern for the SFA with non-uniform burnup. The SFA with uniform burnup of 32 MWd/kg was also examined with a similar pattern of missing fuel.

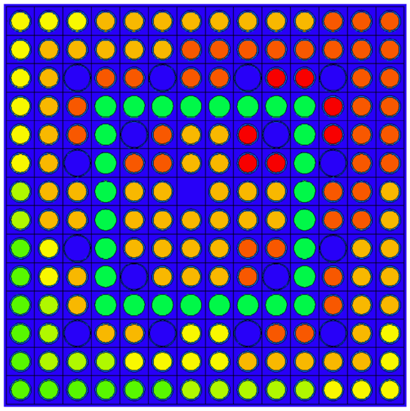

Figure 2. Spent Fuel Assembly with Guide Tube Labels

In addition to the gamma-to-thermal neutron ratios, the normalized (normalized to the maximum value) gamma and thermal neutron signatures are also shown in Figures 3a, 3b, and 3c. The detector locations are as follows: a m, g, and p represent the corner locations; c, j, f, and l represent the center locations, and the rest represent the eight locations along the sides.

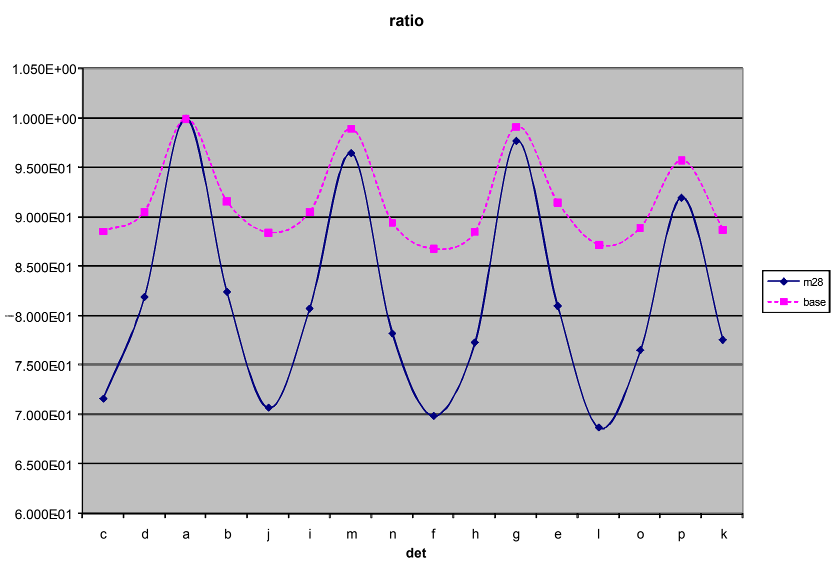

Figure 3a. Comparison of Signatures with 28 Missing Pins-Ratio

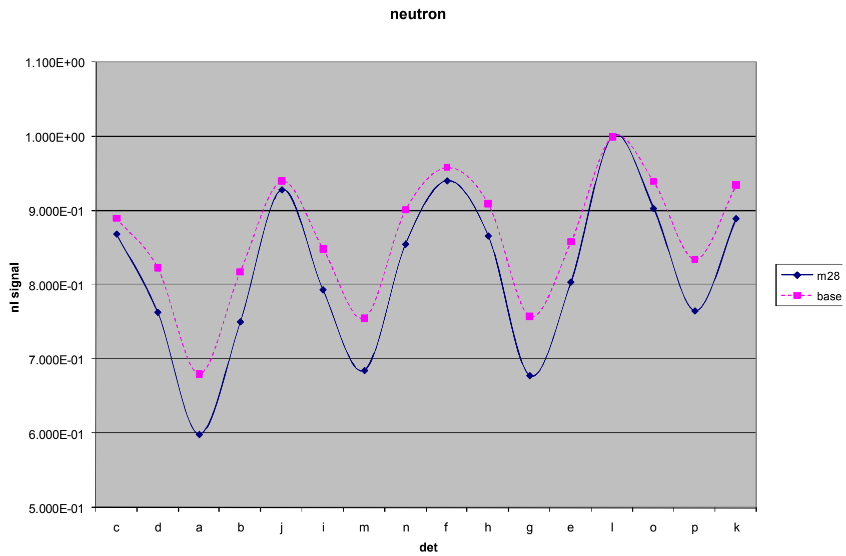

Figure 3b. Comparison of Signatures with 28 Missing Pins-Thermal Neutron

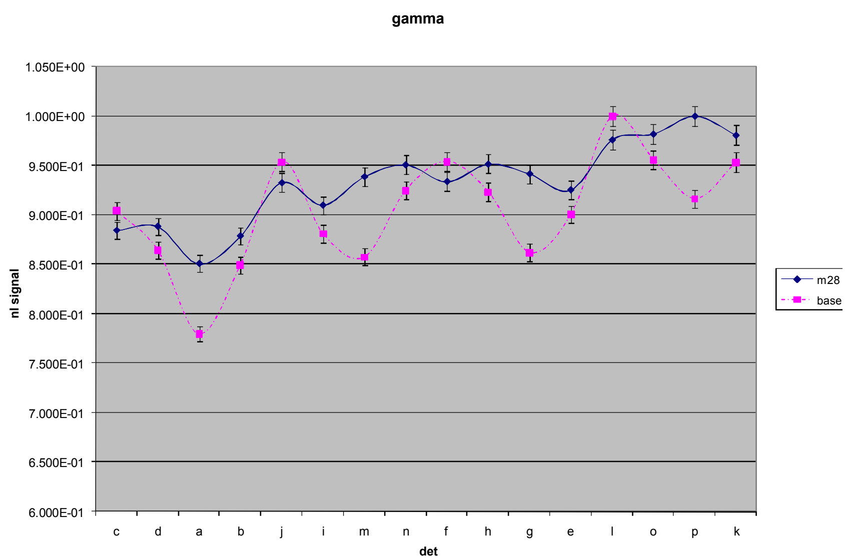

Figure 3c. Comparison of Signatures with 28 Missing Pins-Gamma

The base signature (dashed line) and the signature with missing pins show similar trends for the normalized ratio and thermal neutrons. However, the gamma signature clearly indicates diversion as seen in Figure 3c. The gammas signal is localized since they get absorbed in the high Z, high density fuel and do not travel very far. However, given the pattern of missing fuel in Figure 2, relatively larger numbers migrate to the periphery increasing the gamma signals there. Since the lower left corner of the assembly is the low burnup region and thus a region of the lowest gamma source term, the corner location, ‘a’, sees the smallest impact. Neutrons on the other hand migrate and slow down. The missing pins produce a symmetric thermalizing medium that leads to a relative thermal neutron population that is unchanged from the intact SFA. The normalized ratio signature keeps the shape of the base case, but exhibits steep peak-to-valley ratios, outside of the normal 0.2 range, that can be an indicator of missing pins. Similar results were seen for the SFA with uniform burnup.

ANALYSIS OF IN-SITU ASSEMBLY CASES

This section presents results of analyses for diversion from SFAs with uniform burnup in a 3x3 or 5x5 in-situ condition. As described in an earlier section, the test bundle is surrounded by a checkerboard of low and high burnup SFAs. The diversion pattern consists of clusters of five missing pins symmetric about each of the four four-cluster guide tube locations where the measurements will be taken. Figure 4 shows the pattern in a 5x5 in-situ configuration. This represents a condition where 11% of the fuel pins are missing and is at the typical lower limit of PDET's detection capability. The 3x3 configuration will have the outer 16 SFAs missing.

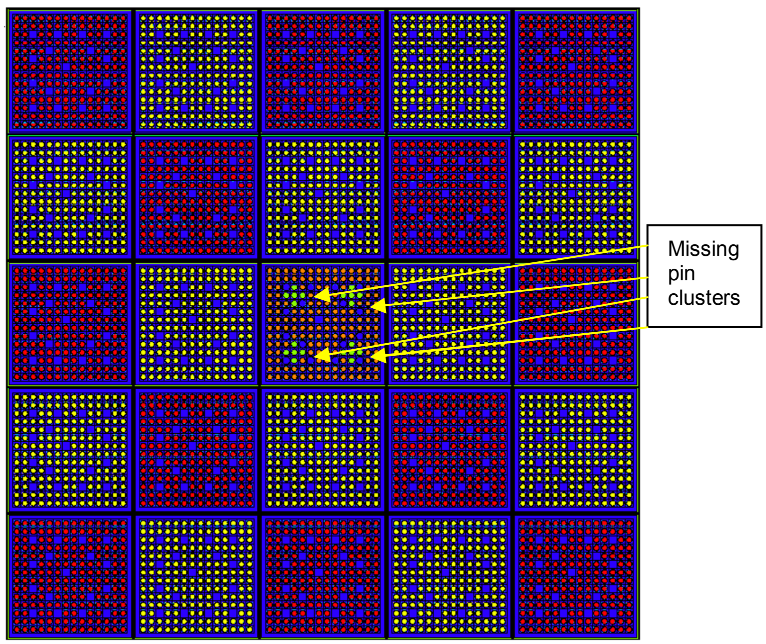

Figure 4. Twenty Missing Pins in 5x5 In-Situ Condition

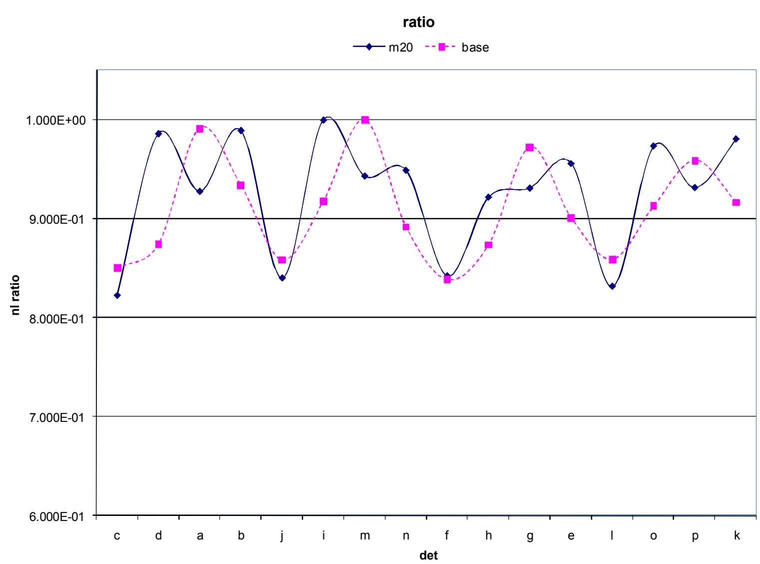

Figure 5a. Comparison of Signatures with 20 Missing Pins-Ratio

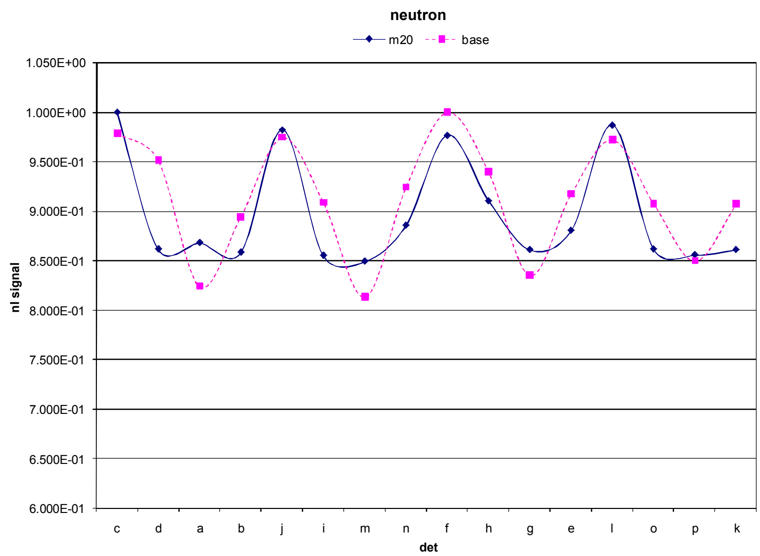

Figure 5b. Comparison of Signatures with 20 Missing Pins-Thermal Neutron

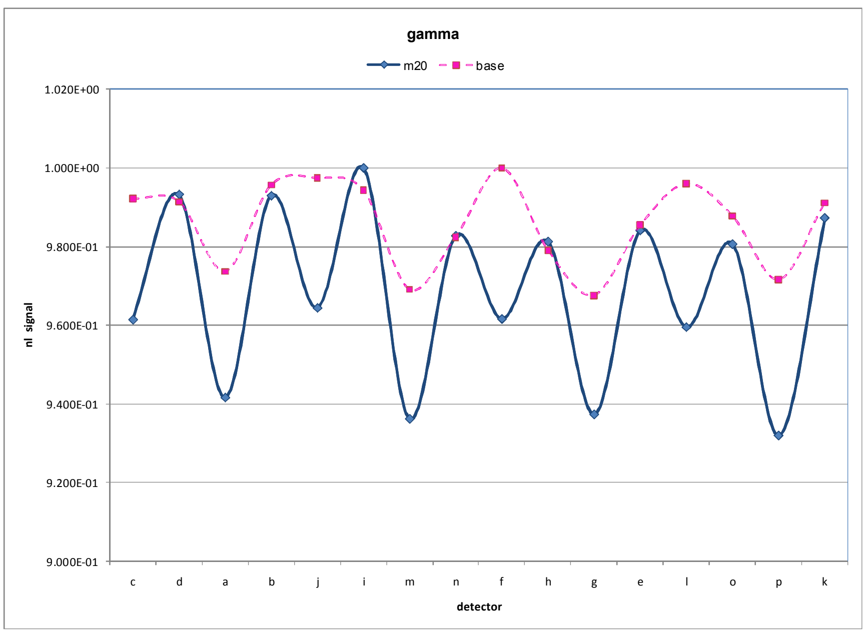

Figure 5c. Comparison of Signatures with 20 Missing Pins-Gamma

Figures 5a, 5b, and 5c show the results from the 5x5 simulation for the normalized ratio, neutron, and gamma signatures, respectively. Once again the neutron signature for the case with 20 missing pins is very similar to the base case whereas the gamma signature shows a visible perturbation in shape. In this case, the ratio also shows a variation in the signature as a result of the missing pins. In this case, the corner and center locations in each cluster of four guide tubes have three adjacent pins missing. This makes the gamma signal lower than usual at the center locations. For the corner locations that normally see the lowest gamma signals the effect is magnified. Examining Figure 5c, the dips in the signature are at these eight locations with the corner locations showing greater dips than those at the center. This effect is less pronounced for the ratio (see Figure 5a) with the perceivable variations seen only at the corners.

The increase in the neutron signal for the 5x5 configuration compared to the 3x3 configuration is an average of 8%. As expected, the very localized gamma signal is not affected by the presence of the additional 16 SFAs in the periphery. Figures 6a and 6b present the comparisons between the 5x5 (dashed line) and 3x3 configurations for the normalized thermal neutron and gamma signatures.

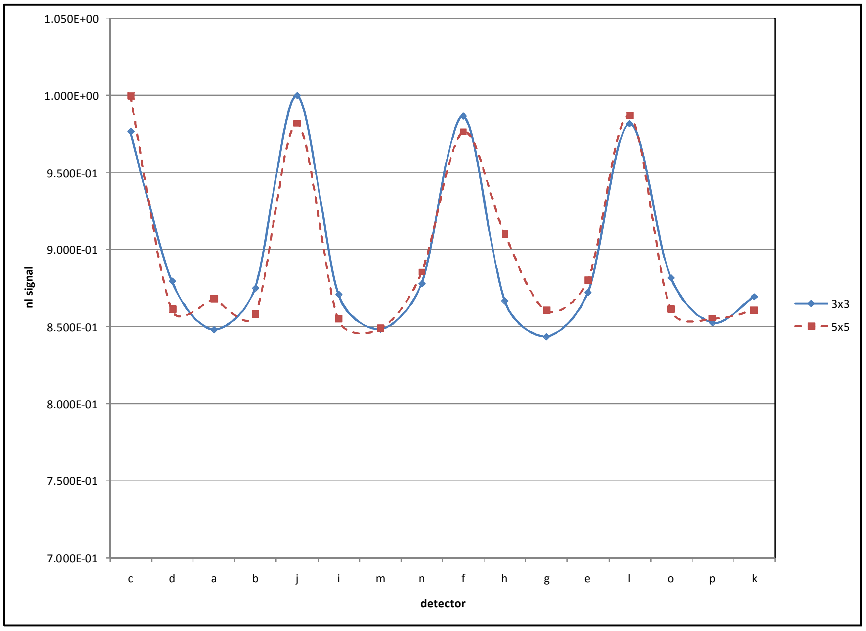

Figure 6a. Comparison of Signatures from 5x5 and 3x3 cases-Thermal Neutron

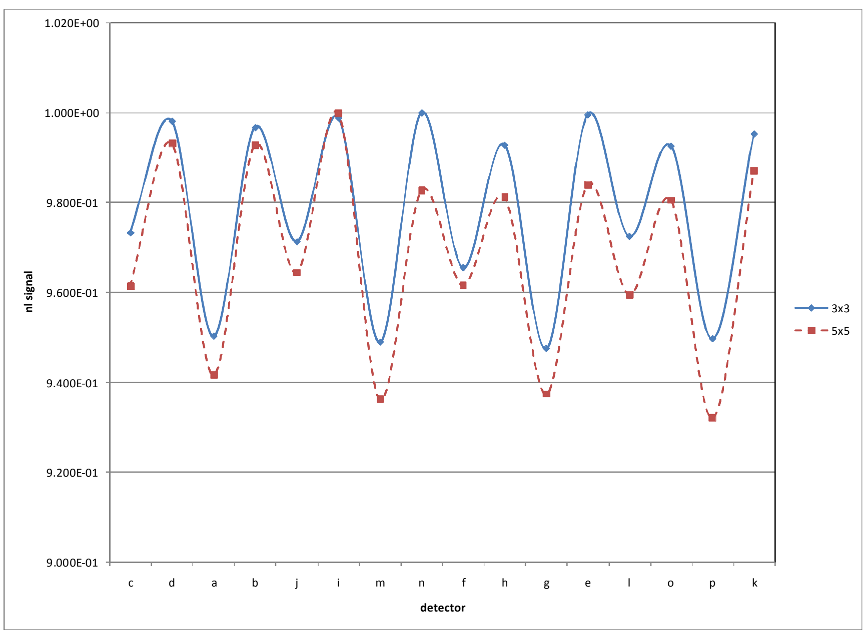

Figure 6b. Comparison of Signatures from 5x5 and 3x3 cases-Gamma

The two figures show that the shapes of the normalized signals are very similar for the two in-situ models.

CONCLUSIONS

The results from the studies presented here as well as other cases examined, indicate that the algorithm developed for PDET is robust enough to detect symmetric pin diversions at the low end of the order of 10-15%. The methodology uses a combination of the normalized gamma-to-thermal neutron ratio as well as the individual normalized thermal neutron and gamma ratios to produce signatures that can visually indicate partial defects in SFAs. The fact that the methodology works for conditions where fuel is not moved from its storage location and does not rely on operator supplied information makes PDET a potentially powerful tool for on-site use in partial defect detection.

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